

# A detached double degenerate with a 1.4 hr orbital period

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## ABSTRACT

We have discovered that the detached double degenerate binary WD 0957-666 has an orbital period of 1.46 hours, rather than the 1.15 day orbital period reported earlier. This is the shortest period example of such a system yet discovered. We obtain a unique period, which fits both our and earlier data. At this period the emission of gravitational radiation will cause the binary to merge within approximately  $2.0 \times 10^8$  years. This system represents a population of short orbital period binaries which will merge within a Hubble time, and so could account for type Ia supernovae, although due to the low mass of both stars ( $0.3$  to  $0.4 M_{\odot}$ ), it is unlikely to become a supernova itself. We have detected the companion star and have measured a mass ratio of  $q = 1.15 \pm 0.10$ . This is the third double degenerate for which  $q$  has been measured and all three have  $q \simeq 1$ , which is in conflict with the predicted mass ratio distribution which peaks at  $0.7$ . This system is viewed close to edge on, and we estimate that the probability of this system undergoing eclipses is 15 %.

**Key words:** binaries: double degenerates : white dwarfs : supernovae progenitors

## 1 INTRODUCTION

One driving force for the detection and study of binary white dwarf, or double degenerate (DD) systems, is the suggested origin of type Ia supernovae (SNIa) involving the coalescence of two white dwarfs (Webbink 1979, Webbink 1984, Iben & Tutukov 1984 and Branch et al 1995). In this scenario, the binary's orbital period decreases due to the emission of gravitational radiation, until the less massive white dwarf is disrupted by tidal forces and is accreted onto its companion (Mochkovitch and Livio 1989). In order to produce a SNIa, the coalesced star probably must exceed the Chandrasekhar mass limit of  $1.4 M_{\odot}$ , which requires the binary to consist of two CO white dwarfs. Helium white dwarf binaries have a total mass of  $0.5 - 0.75 M_{\odot}$  (Webbink 1984) and so it is unlikely that a He+He or even a He+CO binary could contain sufficient mass to produce a SNIa. A second requirement is that the initial orbital period of the binary is short enough that merging may occur within a Hubble time. Branch et al (1995), have considered the different possible progenitors of SNIa, and favour the coalescence of CO white dwarf pairs. However, they stress the need for better determination of the properties of double degenerate systems, and the identification of super-Chandrasekhar mass systems which will merge within a Hubble time.

Surveys sensitive to short orbital period ( $P < 3$  hrs) binaries have been conducted by Robinson & Shafter (1987), and Bragaglia et al (1990). Between them they include a total of 90 DA white dwarfs, including WD 0957-666, which is the only system in their total sample to be conclusively proven to be a short orbital period, double degenerate binary. Foss, Wade, & Green (1991), conducted a survey sensitive to orbital periods between 3 and 10 hours, and found no double degenerates from a sample of 25 white dwarfs. Although the lack of success was disappointing, it may not be surprising as on current estimates only  $1/360^{\text{th}}$  of the total observable white dwarf population are type Ia supernovae progenitors (Iben et al 1997).

Double degenerates develop from main sequence binary systems which undergo 2 separate mass transfer events as each star evolves to fill its Roche lobe. When mass transfer is dynamically unstable, the accreting object is unable to accept all the in-falling material, and a common envelope (CE) is expected to develop. The binary is embedded in this envelope, into which gravitational drag and tidal forces deposit orbital angular momentum and energy from the binary. If sufficient energy is transferred from the binary, the envelope may be ejected. The efficiency with which the envelope is ejected determines the extent to which the orbital period of the binary will be reduced. It is difficult to calculate the

orbital period distribution of double degenerate systems theoretically, and hence to ascertain whether they could be a viable source of SNIa progenitors, primarily due to the uncertainty in the efficiency of envelope ejection. This efficiency is represented by  $\alpha_{CE}$ , the ratio of the envelope's binding energy to the orbital energy lost in ejecting the common envelope. Efficient ejection for which  $\alpha_{CE} = 1$ , results in the orbital period distribution peaking at approximately 12 hours (Yungelson et al 1994). Less efficient ejection will promote mergers and a orbital period distribution dominated by shorter period systems, which will be candidates for SNIa progenitors due to their short merging time scales. The SNIa frequency due to DD mergers calculated by Han et al (1995) is increased by a factor of 1.8 by reducing  $\alpha_{CE}$  from 1 to 0.3, even though the actual birthrate of DD systems falls by a factor 2.2 due to early mergers.

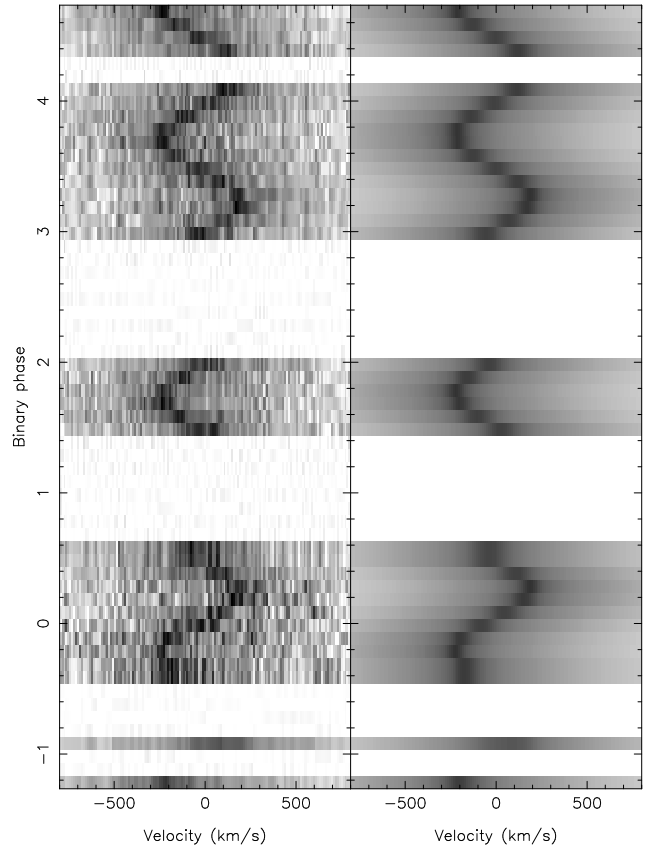
As the value of  $\alpha_{CE}$  has such a large effect on the physical parameters of DD systems, observations of these systems can be used to put tight constraints on the value of  $\alpha_{CE}$ . With this in mind we continued our program to detect DDs from a sample of low mass white dwarfs (Marsh, Dhillon & Duck 1995, and Marsh 1995), and to measure their orbital periods, and if possible their mass ratios.

WD 0957-666 was identified as a DD system by the detection of radial velocity variations resulting from orbital motion. The absence of any main-sequence star features at long wavelengths implied that the companion is also degenerate (Bragaglia et al 1990). We observed it in the hope of being able to detect the companion and hence measure the mass ratio. The only two measured values of the mass ratio for detached double degenerates, L870-2 (Saffer et al 1988) & PG 1101+364 (Marsh 1995), are both around  $q=0.9$ , suggesting a possible flaw in the theoretical models, which peak at 0.7 (Iben et al 1997). Further measurements of mass ratios and orbital periods for DDs, are crucial in order to calibrate the theoretical predictions for close binary evolution.

## 2 OBSERVATIONS

Our data were taken from the 1st to the 3rd of March 1996, with the RGO spectrograph on the 3.9m Anglo-Australian telescope, with seeing ranging from 0.6 to 1.2 arc seconds. The spectra cover 6437 to 6677 Å at a dispersion of 0.23 Å/pixel and a FWHM resolution of 0.7 Å. By observing H $\alpha$  at this resolution we could resolve the sharp non-LTE cores of the two stars.

We initially observed WD 0957-666 with 1400 second exposures, but were surprised when the first two exposures showed a large radial velocity shift of  $\sim 250 \text{ km s}^{-1}$ . Having checked our wavelength scales it was evident that the orbital period was much shorter than the 1.15 days we had expected. We reduced the subsequent exposures to 500 seconds to minimise the effect of smearing on the spectra as the binary components shifted wavelength during the exposures. With hind sight it turns out that the 1400 sec exposures covered  $\sim 28\%$  of the orbital period of binary! The shorter exposures represented a balance between improving the temporal sampling, while maintaining a reasonable signal-to-noise ratio. Typical  $1\sigma$  errors in the radial velocity measurements for the 500s exposures are  $10 \text{ km s}^{-1}$ . A total



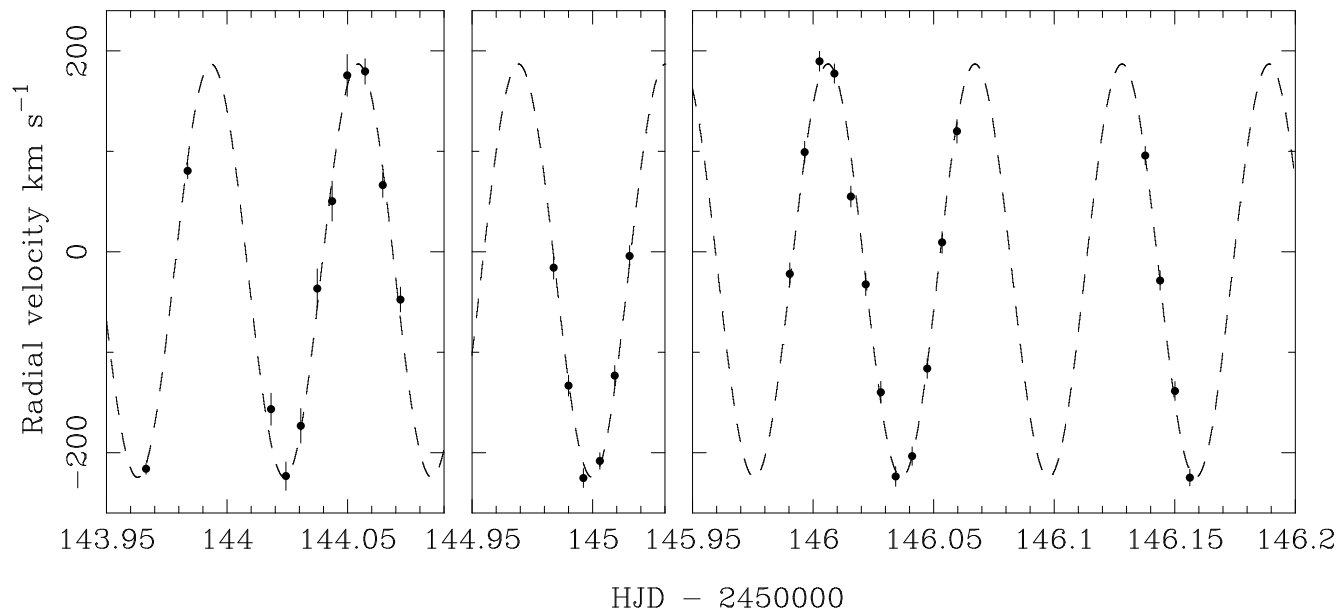
**Figure 1.** In the left-hand panel are the trailed spectra, showing the large ( $\sim 220 \text{ km/s}$ ) radial velocity shifts of the primary. We show the model fit to the data in the right-hand panel.

of 33 spectra were taken over the three nights, including one series which followed a complete orbital cycle.

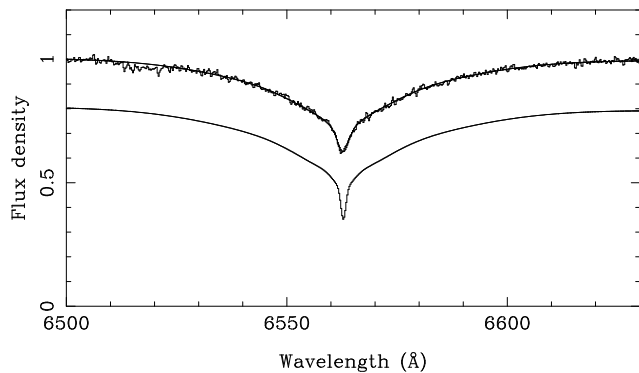
A narrow (0.8 arcsec) slit was used on all nights to reduce radial velocity errors. Each group of three to four object spectra were bracketed by copper-argon arc spectra. The arc and object spectra were extracted at the same position on the detector, and the wavelength scales for the object spectra were derived by interpolating the surrounding pair of arc spectra with time.

## 3 RESULTS

The raw data and the model fits are shown together in figure 1. The measurement of radial velocities followed the procedure described in Marsh et al (1995), but with some adaptations to account for the smearing of the spectra caused by the rapid orbital motion. The spectra were normalised and then averaged. The average was fitted with a model consisting of a straight line and multiple Gaussian components, fixed to have the same velocity for any given spectrum. The FWHMs and heights of the Gaussians were then held fixed while their velocities were allowed to vary. The resultant velocities were fitted with a circular orbit. The velocities from this orbital fit were then removed from the spectra which were then re-averaged (Fig 2). The cycle of averaging, fitting, removing velocities and then re-averaging was repeated



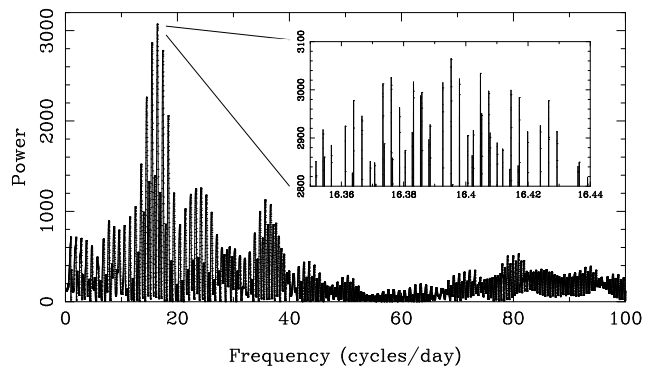
**Figure 3.** The measured radial velocities for each of our 33 spectra, along with the circular orbit fit.



**Figure 2.** At the top we show the mean spectrum of WD 0957-666 corrected for orbital motion, along with the model fit. Telluric absorption can be seen around 6520 Å. Off-set below this is the true model profile, unaffected by the smearing caused by orbital motion during the exposures.

three times. As a result of cycling the fitting process, the fit sharpened considerably, requiring the introduction of more Gaussian components. Four Gaussians were used in the final fit, and the radial velocity measurements converged to stable values, with a semi-amplitude velocity of  $K_1 = 196 \text{ km s}^{-1}$ , see figure 3.

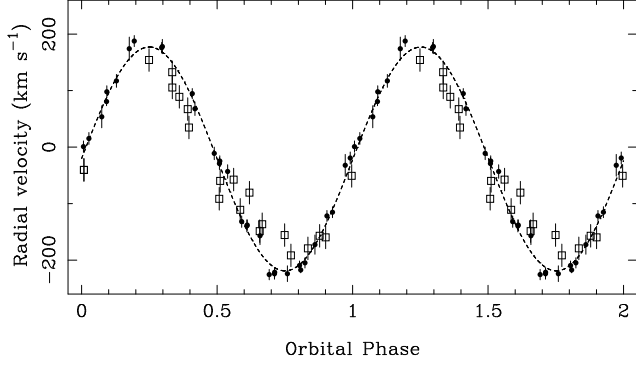
To refine the orbital period, we re-measured radial velocities of  $H_\beta$  in 24 spectra taken between Jan 1988 and Jan 1990, (Bragaglia et al 1990). The Scargle periodogram in figure 4 shows how the extension of the observational baseline can increase the accuracy with which the orbital period can be determined. The combined data set of measured radial velocities was fitted with periods derived from many of the most likely orbital period aliases shown in the inset of figure 4. The  $\chi^2$  values for the orbital fits rose sharply for



**Figure 4.** A periodogram of our data shows the dominance of a 16 cycles/day orbit. The extension of the observational baseline with the inclusion of Bragaglia et al's data allows the different orbital aliases to be resolved, as shown in the inset.

periods other than that represented by the peak alias in the periodogram, ruling out any other orbital periods.

At this stage we adapted the fitting routine to include the effects of smearing due to orbital motion. The exposure time and orbital period were used to calculate the phase width covered by each spectrum. Each model fit was then calculated by trapezoidal integration, accounting for the orbital motion during the exposure. The inclusion of the smearing parameter had the expected effect of further sharpening the fits, and of increasing the semi-amplitude of the circular orbital fit to  $K_1 = 205 \text{ km s}^{-1}$ . The fitting cycle was repeated three more times with smearing accounted for, until the radial velocity measurements converged on stable values. The circular orbit fit to our and Bragaglia et al's data is shown in figure 5.



**Figure 5.** The phase folded radial velocity measurements and circular orbit fit for WD 0957-666. The solid circles represent our data while the squares represent measurements from Bragaglia's data.

**Table 1.** Model fitting parameters

| Constant | Gaussian | Star | FWHM(Å) | Height (mJy) |
|----------|----------|------|---------|--------------|
| 1.017    | 1        | 1    | 53.4    | -0.150       |
|          | 2        | 1    | 20.2    | -0.109       |
|          | 3        | 1    | 4.91    | -0.062       |
|          | 4        | 1    | 1.30    | -0.127       |
|          | 1        | 2    | 40.7    | -0.041       |
|          | 2        | 2    | 4.97    | -0.023       |

### 3.1 Detection of the Companion

So far, only the primary star had been modelled, as there was no obvious sign of the secondary star, in either individual spectra, or the trailed spectra (Fig 1). Detecting the companion is highly desirable as it allows calculation of the mass and luminosity ratios of the binary.

We subtracted the model fits from the data and then phase binned the residuals to increase the S/N. We show the results in figure 6. Although very faint, the companion has been detected. As the companion appears in absorption it confirms the double degenerate nature of WD 0957-666. When measured by eye, the companion appears to have a semi-amplitude  $K_2$ , of approximately  $200 \text{ km s}^{-1}$ , and appears to be  $180^\circ$  out of phase with the primary as expected.

### 3.2 Orbit fitting to the companion

Having detect the companion, we determined its radial velocity semi-amplitude by including two further Gaussian components to the previously used model fit, to represent the secondary star. As no individual spectrum shows any strong evidence of the companion, we applied the fit to all the spectra, fitting FWHM, heights and orbital parameters simultaneously. The final gaussian model fitting parameters are shown in table 1. The fitting procedure converged to give stable values for the companion's orbital parameters, as shown in table 2. Our best fit value of  $K_2$  was  $252.4 \pm 21.5 \text{ km s}^{-1}$ . The inclusion of the Gaussian components to model the companion star, increased the radial velocity semi-amplitude of the primary  $K_1$  to  $219.8 \pm 1.9 \text{ km s}^{-1}$ , as the fit to the primary star was no longer pulled to lower velocities by the presence of the unaccounted for secondary star.

**Table 2.** Circular orbit fit parameters

|                                     |                              |
|-------------------------------------|------------------------------|
| $\chi^2/DofF$                       | 0.969                        |
| N                                   | 33                           |
| $\gamma \text{ (km s}^{-1}\text{)}$ | $-18.7 \pm 1.4$              |
| $K_1 \text{ (km s}^{-1}\text{)}$    | $219.8 \pm 1.9$              |
| $K_2 \text{ (km s}^{-1}\text{)}$    | $252.4 \pm 21.5$             |
| Orbital Period (d)                  | $0.0609931806 \pm 8.4^{-10}$ |
| $T_o$                               | $2450145.3796 \pm 1^{-4}$    |

## 4 DISCUSSION

### 4.1 The mass of the companion

The mass ratio, as defined below, may be calculated directly using the semi-amplitude velocities found with the fitting process. Using  $K_1 = 220 \pm 2 \text{ km s}^{-1}$  and  $K_2 = 252 \pm 21 \text{ km s}^{-1}$  we calculate  $q = 1.15 \pm 0.10$ .

$$q = \frac{M_1}{M_2} = \frac{K_2}{K_1}$$

Bragaglia et al (1995) determined the surface gravity and effective temperature of the primary star to be  $\log(g) = 7.285 \pm 0.082$  and  $T_{eff} = 27047 \pm 398 \text{ K}$  respectively. They calculated the primary star mass to be  $M_1 = 0.335 \pm 0.018 M_\odot$  using models with carbon-oxygen cores. Bergeron et al (1992) have shown that the zero temperature mass-radius relationships of Hamada & Salpeter (1961) are not significantly different for carbon and helium configurations at this mass. However, using new evolutionary models with helium core configurations (Althaus & Benvenuto 1997) that include finite temperature effects (which are most significant for low mass stars) we estimate that  $M_1 = 0.37 \pm 0.02 M_\odot$ . This leads to a mass determination for the secondary star of  $M_2 = 0.32 \pm 0.03 M_\odot$ .

Although we cannot calculate the individual masses due to the unknown inclination of the system,  $i$ , we can calculate the following quantities.

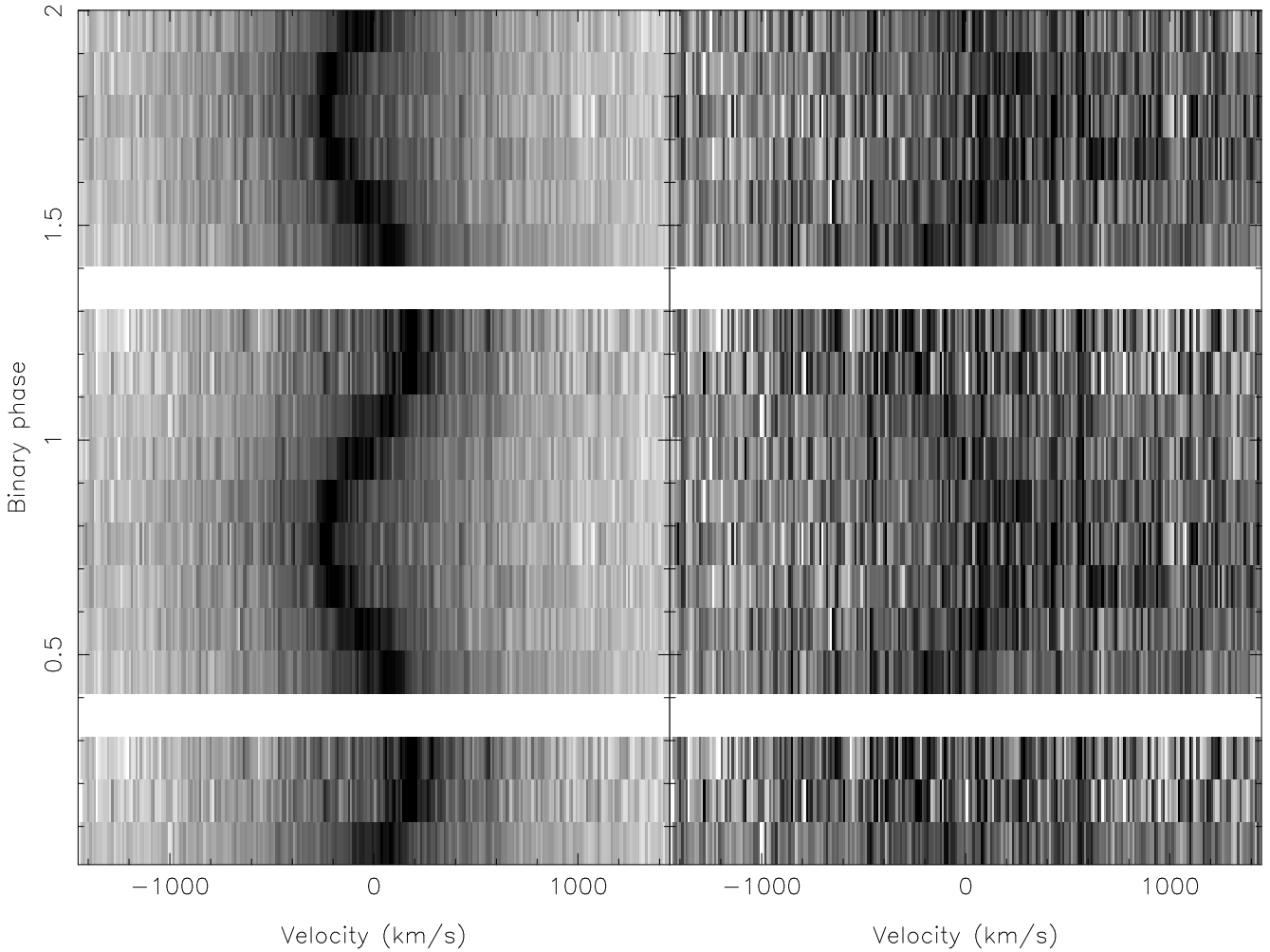
$$M_1 \sin^3 i = \frac{P}{2\pi G} (K_1 + K_2)^2 K_2 = 0.356 \pm 0.066 M_\odot$$

$$M_2 \sin^3 i = \frac{P}{2\pi G} (K_1 + K_2)^2 K_1 = 0.310 \pm 0.033 M_\odot$$

For the above value of  $M_1 \sin^3 i$  to be consistent with the mass  $M_1 = 0.37 \pm 0.02 M_\odot$ ,  $\sin i \simeq 1$ , and so the system must be observed at a high inclination. A calculation yields  $\sin i = 0.99 \pm 0.11$ . The fact that the system is viewed close to edge on, raises the tantalizing possibility that this system may undergo eclipses.

### 4.2 Mass ratios of double degenerates

The mass ratio estimate is interesting as it implies that the system could have previously been through an Algol-like phase of conservative mass transfer (Sarna et al 1996). A value of  $q > 1$  means the brightest white dwarf is also the most massive. It must then be at a higher temperature, and hence younger than its companion to be so visible. The apparent paradox is that the mass of each white dwarf is effectively the mass of the degenerate helium core of its progenitor star at the point when it fills its Roche lobe, which depends on the size of the semi-major axis of the binary at that time. Roche lobe overflow from a giant with deep convective layers usually leads to a common envelope phase,



**Figure 6.** In the left hand panel we show the phase binned raw spectra, which shows the dominant primary star. The right hand panel contains the residual from subtracting the model fit of the primary star, from the data. The faint secondary star is detected with a semi-amplitude of approximately 250 km/sec, in anti-phase to the primary star. Some weak telluric features appear as vertical lines in this panel.

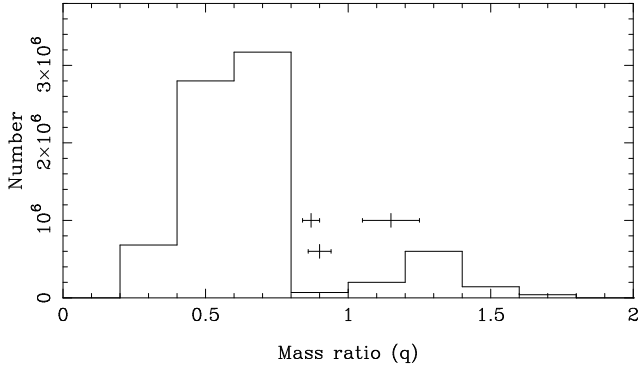
resulting in orbit shrinkage as the envelope is ejected at the expense of orbital energy. Hence by the time the secondary star (the progenitor of the primary WD) evolves to fill its Roche lobe, the orbital separation should be significantly smaller and hence so should the degenerate core of the giant, and the resulting white dwarf mass. For the youngest white dwarf to be also the most massive, the system must have undergone a period of conservative mass transfer, during which the initial mass ratio was reversed so that the most evolved star became the least massive, and produced the least massive white dwarf.

There are only two other DD systems which have measured mass ratios, L870-2 for which  $q = 0.90 \pm 0.04$  (Saffer et al 1988) and PG 1101+364 for which  $q = 0.87 \pm 0.03$  (Marsh 1995). This is unexpected as theoretical predictions suggest a peak at  $q = 0.7$ , see figure 7. Having three out of three measured values in the wing of the distribution profile, suggests a flaw in the theoretical models. A more accurate determination of  $q$  for this, and other DD systems is needed to confirm whether this tendency for the mass ratio to be close to 1 is

just coincidental, or whether the theoretical predictions are inaccurate.

### 4.3 The possibility of eclipses

We conducted Monte Carlo simulations to investigate the probability of eclipses in this binary. We took  $\log T_{eff} = 4.432$  and  $\log g = 7.285$  from Bragaglia et al (1995), and interpolated between values given in table 6 of Althaus and Benvenuto (1997), to give the mass radius relationship. We estimate that the probability of this binary system undergoing eclipses is 15 %. The significance of an eclipsing double degenerate system is that it could be used to check the accuracy of the equation for the emission of gravitational radiation, as well as the mass-radius relationship for white dwarfs.



**Figure 7.** The theoretical mass ratio distribution for close double degenerate binaries with helium white dwarfs. (Iben et al 1997) The tick marks show the only three measured mass ratios and their associated errors.

#### 4.4 The luminosity ratio

We can estimate the brightness of the companion by assuming that its line profile has the same shape as that of the primary star. The FWHMs of the Gaussian components, and their relative strengths, were fixed to be equal for both stars, while the overall strength of each star was allowed to vary. These fits were then applied to the data, having fixed the orbits of both stars. We estimate that the luminosity ratio,  $L_1/L_2 \simeq 5.1$ . The assumption of similar profile shapes for both stars is an obvious simplification, as the companion is much cooler than the primary star, and so might have a different profile. In principle this could be accounted for, but is beyond the scope of this investigation.

#### 4.5 The evolution of WD 0957-666, past, present and future

The previous evolutionary pathway of this system is constrained to some extent by the mass ratio measurements. It seems probable that the progenitors of these white dwarfs underwent an Algol-like phase in the past, resulting in the reversal of the mass ratio. The time passed since the binary emerged from the last common envelope phase can be estimated from the primary's temperature  $T_{eff} = 27047$  K (Bragaglia et al 1995). We estimate that the system has been in its present state for  $10^7$  yrs (Marsh et al 1995). This is only a fraction of the merging time scale (see below) and hence the orbital period of this system will not have changed appreciably since its formation.

The only changes the system will now be undergoing are the continual cooling of both white dwarfs, and the reduction of the orbital separation and orbital period due to the emission of gravitational radiation. Given the already short orbital period of this system, the stars will merge rapidly, even considering their low masses. The time required to merge due to gravitational radiation emission is given by

$$\tau_m = 1.00 \times 10^7 \frac{(M_1 + M_2)^{\frac{1}{3}}}{M_1 M_2} P^{\frac{8}{3}} \text{yr}$$

with the orbital period given in hours, and the masses in solar units. Taking  $M_1 = 0.37M_\odot$ ,  $M_2 = 0.32M_\odot$  and  $P = 1.46$  hrs, we calculate that the binary will merge within  $2.0$

$\times 10^8$  yrs. WD 0957-666 is a system which will merge well within one Hubble time.

The future evolution of this system is dependent on the outcome of the merging process. Given the limits we have placed on the mass ratio of this system, it is not possible that the companion could be massive enough for the merged object to exceed the Chandrasekar mass limit. Hence it is unlikely to produce a SNIa, although the existence of sub-Chandrasekar mass progenitors has not been ruled out (Livne & Arnett 1995). The most likely outcome will be the formation of a helium subdwarf star (Webbink 1984).

#### 4.6 Short orbital period DDs as SNIa progenitors

The detection of this short orbital period system, offers more observational proof that these systems can be born with very short ( $P < 4$ hrs) orbital periods, as predicted theoretically. A population of such systems will need to exist if merging white dwarfs are SNIa progenitors. Also, by populating the short and long period wings of the theoretical orbital period distribution, we can improve the estimated value for  $\alpha_{CE}$ . Choosing different values of  $\alpha_{CE}$  shifts the relative position of the theoretical orbital period distribution, with an increase in  $\alpha_{CE}$  shifting the distribution to longer orbital periods. Improving theoretical predictions, and the parameters like  $\alpha_{CE}$  on which they are based, will help to determine whether DDs exist in the right numbers, and with the right periods and masses to be the progenitors of SNIa.

### 5 CONCLUSIONS

We have determined the orbital period for the double lined, detached double degenerate white dwarf WD 0957-666. At 1.46 hours it's the shortest period system of its kind yet found. The emission of gravitational radiation will force the binary to merge within only  $2.0 \times 10^8$  years, but the combined mass will not be sufficient to make this system a SNIa progenitor candidate. We have measured the mass ratio of the binary to be  $q = 1.15 \pm 0.10$ . All three such systems for which  $q$  has been measured, have a value close to 1. It suggests that the theoretical mass ratio distribution which peaks at  $q = 0.7$ , may be in trouble. The measured semi-amplitudes of the two stars, along with the spectroscopic mass of the primary, imply that the system is viewed at an inclination close to  $90^\circ$ , with a 15% probability that the binary is eclipsing.

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